

A DUST AGGREGATION AND CONCENTRATION SYSTEM (DACS) FOR THE MICROGRAVITY SPACE ENVIRONMENT

F.J. Giovane, Space Science Division, Naval Research Laboratory, Washington, DC 20375-5320,
giovane@nrl.navy.mil

J. Blum, Astrophysical Institute and University Observatory, University of Jena, Jena, Germany
blum@astro.uni-jena.de

INTRODUCTION

The formation of planetary systems is a multi-stage process that has fundamental importance to astrophysics and the understanding about origins of life. In the early stages of the proto-solar nebula fine dispersed dust grains accumulate into larger and larger bodies through frequent collisions between the dust grains due to Brownian motion, differential drift velocities, and decoupling from gas turbulence until their internal gravity becomes the dominant source for their further growth. An understanding of the changing morphologies and light scattering characteristics of aggregated dust under various growth conditions is needed to better interpret astronomical observations of dust in star forming regions. However, the direct simulation of the long-term behavior of a cloud of dust grains under thermal motion, as in the very early stages of the proto-solar nebula, is not possible in a terrestrial laboratory. Even in levitation-compensated experimental setups the relative velocity is determined by the Earth's gravity field, and a velocity field, which simulates the motion of astronomical dust grains, is not feasible.

It was with the goal of developing a system for observing the self-interaction of a cloud of dust grains that the present international team of investigators joined together in the Cosmic Dust Aggregation, (CODAG) Microgravity Experiment. CODAG, when it flies later this year, will for the first time undertake the study of light scattering from a cloud of astrophysical relevant dust aggregating under controlled conditions. Its observation time is however limited by the diffusion time of dust to the walls of the stationary chamber. A solution was therefore sought to overcome this deficiency, that is to dramatically extend the duration with which dust particles can be suspended and concentrated. It was felt that if the duration could be extended the formation of larger aggregates will result, and essential information on one of the fundamental steps in planetary formation obtained.

Based on the lessons learned from the CODAG, and from experience gained in drop tower tests, parabolic flights, and ground experiments conducted at the University of Jena (UJena), Germany, the concept for the Dust Aggregation and Concentration System

(DACS) for the microgravity space environment was developed.

The DACS concept will allow the morphology of a dust cloud to be studied as the individual particles aggregate and concentrate. The system represents a unique opportunity to study in situ astrophysical conditions similar to those experienced in the formation and evolution of the proto-solar nebula. The DACS project team, whose principal interests are in astrophysics will naturally pursue this interesting area. However, it is expected that the unique opportunity afforded by the DACS to hold dust particles and aerosols in suspension for extended periods, and the instruments ability to concentrate these particles during suspension will be of interest to scientist in other fields such as fluid dynamics, material and biological science, etc.

1.1 Objectives

The following are the principal objectives of the Dust Aggregation and Concentration System, DACS definition project. These goals are fully within the context of NASA's Human Exploration and Development of Space Enterprise, and they are directly responsive to the objectives of NASA's "Origins" theme and to the President's new Civilian Space Policy.

The following objectives relate to an optically thin particle cloud in a low gas pressure and microgravity environment, and obviously can not be achieved until the proposed investigation is completed, and a flight unit built and flown. The following objectives therefore represent the end goals of the DACS development effort.

- a. Grow larger aggregates than is presently possible in a stationary chamber.
- b. Make precise light scattering measurement of the evolving dust aggregate cloud.
- c. Acquire greater understanding of the dust concentration mechanism and the maximum concentration achievable.
- d. Explore the instabilities at the interface of gas to dust dominated regions.

During the course of the project we seek to define the physical parameters that control the behavior of the suspended dust cloud and define the require-

ments for those instruments best suited to gather data during the aggregation process

At the completion of this definition study it is expected that we will have obtained:

- A. A practical understanding of the optical induced thermo-phoresis effect for both single and aggregated particles.
- B. Computer simulation tools, validated by laboratory tests, to better predict the behavior of dust and low pressure gas in a microgravity environment.
- C. A sufficiently detailed design of the DACS and its science requirements to expeditiously develop a flight instrument.

1.2 Dust Aggregation in Astrophysics

There are four major points that distinguish terrestrial dust and dust aggregation from the process occurring in a pre-solar nebula. It is generally believed that under the conditions of the preplanetary nebula that:

1. Planetesimals agglomerate from dust whose initial grain size is typically believed to be less than 1 mm in radius.
2. Dust grains are principally restricted to 4 groups of uncharged and un-magnetized particles: (1) silicates, (2) carbonaceous matter, (3) organics, and (4) ices (mainly water).
3. Dust is embedded in a thin gas environment; the gas flow around the particles is molecular and not viscous.
4. Aggregation in space is always ballistic and not diffusive - i.e. particles are on linear trajectories when colliding. This yields different fractal structures of the aggregates as compared to the diffusive case.

Under these conditions our ability to use terrestrial models for the dust aggregation process is very limited. As a consequence, there have been only three dust experiments known to us that deal with astrophysically relevant environments:

- I. Praburam & Coree (1995) have investigated the growth of carbon particles in a plasma environment which is not representative of the young solar system (see 2 above);
- II. Higuchi & Sugiura (1993) investigated the distribution of fluffy aggregates floating in the air under relatively uncontrolled and unregulated environmental conditions.
- III. Nuth et al. (1994) have observed the magnetically enhanced coagulation of metal particles. Although this is a useful study to see

how such particles might come together, it is a very unlikely mechanism for dust aggregation in the early solar system.

The characteristics of these dust experiments, however, do not resemble the conditions that are believed to exist in the early solar system.

Consequently, until recently dust aggregation work remained mainly the subject of theoretical and computational studies. Four years ago one of us, Blum, began a movement towards solving the astrophysics questions. He initiated a laboratory at the University of Jena (UJena), dedicated to dust aggregation experiments that fulfill the conditions 1 through 4 given above. Giovane and B.A. Gustafson (U of Florida) joined him three years ago to expand the CODAG experiment to include the study of light scattering from the aggregated particle cloud. Over the years Blum's team at UJena have acquired extensive experience in the microgravity area, in particle generation, and in particle suspension. Several auxiliary devices were specifically invented there for this purpose. Much of the auxiliary equipment that is envisioned to be part of DACS derives from these developmental efforts. Among these successes was a de-agglomeration device for the production of monodispersed, high number density aerosols under low vacuum and microgravity conditions, Blum et al. (1996a) and the laboratory prototype of the DACS chamber.

The work at UJena led to the detailed study of Brownian motion of micron sized dust grains and aggregates in microgravity, Blum et al (1996b), in conditions approximating those of the very early pre-solar nebular. Dust aggregation in a turbulent gas environment and in a levitation tube were observed and aggregate size distributions were measured for large dust aggregates composed of up to one thousand particles each, Wurm & Blum, (submitted 1997)). Such aggregated particles are illustrated in Figure 1. In another laboratory experiment, the critical velocity below which sticking occurs and above which particles rebound was determined. Poppe & Blum (1996) showed that the critical sticking velocity is a factor of 6 greater than theory. Recent results of laboratory experiments are summarized in Blum (1997). These ground based experiments, including parabolic and drop tower tests have contributed to the technique and understanding of what is required to achieve large aggregate particles. However they are in themselves incapable of providing the environment required to meet the DAC Experiments objectives.



Figure 1. Examples of aggregated 1.95- μ m particles generated in the UJena Rotating Chamber. Bar at bottom of the figure is 100 microns in length.

Long period suspension of dust is needed for deeper insight into the astrophysical questions. The CODAG Experiment, which allows the Brownian motion driven dust to aggregate, is inadequate to provide the suspension time needed. The diffusion and drift time of the dust in a stationary chamber, even in a microgravity environment, severely limits the duration that particles can remain suspended. However, it is from the CODAG experience and the work done at UJena that a new approach involving a rotating chamber has emerged. We will adapt this approach in the DACS, and perfect it to the degree needed to achieve a space experiment that will meet the proposed objectives. The approach that we will take will allow extended periods of particle suspension, and thereby very greatly increase the duration of the dust aggregation. It is believed that the process can be continued right through to macroscopic agglomerates.

1.3 The Rotating Chamber Concept

In order to overcome some of the limitations in the duration over which the aerosols can be sustained in a 1 g laboratory environment, a rotating chamber was developed at UJena to take advantage of the angular velocity effect on the motion of the dust. This chamber is illustrated in Figure 2.

With this apparatus it has been shown that a dust cloud can be suspended for several minutes in an earth gravity field. The resulting observations corresponds very well with the time predicted by calculations which take into account the centrifugal forces driving the particles to the chamber walls. In the earth's gravitation field, the relative motion of the

dust particles in the chamber is due to residual sedimentation and leads to rapid aggregation of the dust particles. This rapid aggregation and the limited time that the dust can be suspended make it necessary to bring a rotating chamber into space and the microgravity environment in order to achieve our goals.



Figure 2. The rotating chamber at the University of Jena with associated apparatus. A microscope and fast CCD Camera are illustrated at left looking into the chamber.

DISCUSSION

2.1 The Dust Aggregation and Concentration System

The CODAG microgravity experiment, as we have noted, is limited by the grain diffusion and drift to the chamber walls. Therefore the growth of very large aggregates over a long period of time, requires an alternate approach. The fundamental success of the UJena laboratory rotating chamber in supporting a cloud for several minutes led us to believe that it can be modified for the microgravity environment to achieve the required very long period suspension that will allow the aggregation of a very large number of dust grains. The most prominent change required in the microgravity environment is in the introduction of a one dimensional external force field with an associated field gradient. The field gradient is required to allow particles moving under the influence of the gas in the rotating chamber to move faster in one half of the drum chamber than in the other half. If the resulting force moving the particles towards concentration is stronger than the dispersive centrifugal forces due to the rotation induced by the gas, then the particles will be concentrated in an effective way. The

concentration effect will be strongest in a large chamber with slow rotational velocities. In other words, for the right combination of forces, those created by the rotating gas on the particles in the drum and another force acting in part counter to this motion, there will be a net motion of particles towards an equilibrium point removed from the center of rotation. If this force is greater than the centrifugal force, which tends to drive the particles outward, the particles will concentrate.

We have been studying potential candidates for the simulation of the vertical component of the pre-planetary gravitational field. As we excluded for astrophysical reasons charged and magnetic particles, and thus electrical or magnetic fields, the only remaining and practical externally applicable acceleration field for the rotating chamber experiments seems to be the light induced phoresis force.

One might argue that in order to simulate the concentration effect in pre-solar turbulent eddies, the use of tidal forces or any other inertial force would be preferred. However, any tidal force outside the Earth's surface acts in just the wrong direction: in general, such forces become stronger in the direction in which the forces act. The same holds for centrifugal forces as an example of an inertial force. Only inside the Earth are the gravitational field and its gradient anti-parallel. Unfortunately, the gravitational gradient is almost infinitely small. Thus, the light-induced phoresis force appears to be the only solution available to us to create the kind of force needed, that is if the conditions to exclude charged and magnetic particles and, therefore electrical or magnetic fields, are adhered to.

This phoresis force is created by illuminating a cloud of dust particles, which are embedded in a rarefied gas environment. The light interaction with the particle results in the gas surrounding the particle being differentially heated. This results in the molecules with slightly greater temperature, and therefore higher velocities, creating a differential force on the dust grain. The phenomena was originally observed by Ehrenhaft in the early part of this century (ca. 1910). Since that time several investigators have studied it. F. Deguillon (1950) suspended particles by electrical fields while illuminated. He observed that the particles move both towards and away from the light source depending on their optical characteristics. Orr and Keng (1964) measured both these photophoresis effects in a chamber where the light controlled the rate of fall of the particle. When the particle moves towards the light source the phoresis was termed negative: when it move away it was termed positive. Kerker and Cooke (1982) provided a realis-

tic model of the force on particles in the free-molecular regime.

One of us (Blum) has observed such a motion in a cloud of optically thin transparent particles during microgravity parabolic flight experiments. In the case of the transparent particles, which were observed to travel towards the illumination source, we could properly term this an optically induced negative thermo-phoresis effect. However, both for simplicity and to maintain the more traditional terminology we will refer to the effect as the "photophoresis" effect and the force that causes the effect the "photophoresis force" or "photophoretic" force. It should be kept in mind that the motion is due to a differential heating of the gas and not directly to the photons of the light source impacting the particles.

Since the direction of the force is not directly material to its application in DACS (either positive or negative photophoretic force are suitable) we will not differentiate between the two in the following discussion except when necessary. What is important is the light's wavelength and how it is focused, as these determine the strength of the photophoretic force field for a particular dust particle.

Let us now look with greater detail into the process that might be created in a microgravity environment and its relationship to the conditions that exist in the pre-solar nebula. Dust grains in the pre-solar nebula may be incorporated into turbulent gas eddies. A dust particle within such an eddy is not only subject to gas drag (friction) forces but also to centrifugal forces which tend to drive the grains out of the eddy. However, an additional vertical (perpendicular to the solar nebula's midplane) gravitational field is present which results in a sedimentation of the grains towards the midplane of the solar nebula. Due to the large extent of the eddies (typically of the order of the half-thickness of the disk), the particles are sedimenting faster in the upper half of the turbulent eddy than in the lower half (closer to the midplane of the nebula). It has been shown by Klahr & Henning (1997) that for typical eddy sizes and gas densities in the solar nebula, a net concentration by factors exceeding 100 can be reached for grain sizes of mm and below.

The effect of particle concentration in a rotating cylindrical chamber depends strongly on the gradient of the one dimensional photophoretic force field which is superimposed on the centrifugal force field due to the rotation of the chamber. A force field of the form given in Equation. 2 (below) can be deconvolved into a constant mean acceleration $-g$ and into a harmonic component $-\Omega^2 z$ which acts like a spring and drives the particles towards the equilibrium point

x_s (see Equation. 3). If the gradient of the harmonic acceleration $-\Omega^2$ is larger than the centrifugal acceleration gradient ω^2 , the net concentration effect is stronger than the dispersion of the grains and particles are concentrated in an effective way. This, in some measure, mimics the sedimenting process in the pre-solar nebula.

2.2 Numerical Modeling

In order to effectively model the rotating chamber system numerically, a particle tracking scheme fully coupled to the gas phase of the system will be employed. In this scheme, the motion of each dust particle is determined by a governing equation of motion which directly takes into account the local forces, such as particle inertia and drag, as well as external forces such as the photophoretic force. Thus no generalizations concerning particle-particle and gas-particle interactions need to be made and individual particle trajectories at any given instant are known. Similarly, the fluid phase is modeled in such a manner to account for flow modulations through the disturbance flow generated by the dispersed particle phase. This characteristic is quite desirable as little is known about the gas phase as the dust particles congregate at the equilibrium point and the flow is modified.

In a similar manner the photophoresis effect will be modeled. Here we will introduce theoretical and laboratory determined light scattering models to better explain the effect and its changes with particle characteristic. Laboratory tests will be very closely linked with the fluid dynamic models, so that the result of one will determine the direction of study of the other.

2.3 Conditions for Aggregation and Concentration.

Consider a cylindrical vacuum chamber, rotating at an angular velocity ω in a gradient field. The cylinder is rotated about its horizontal symmetry axis (as illustrated in Figure 3), into which a cloud of particles and gas are injected. The injected gas quickly assumes the rotational motion of the chamber. The gas rotation is stiff, with a constant angular velocity tied to that of the chamber. On the side, where the rotating gas moves against the gradient field, there is an equilibrium point at which the motion induced by the gas equals the velocity of the dust due to the gradient field. The particles are levitated near this equilibrium point, with the particles orbiting about that point.

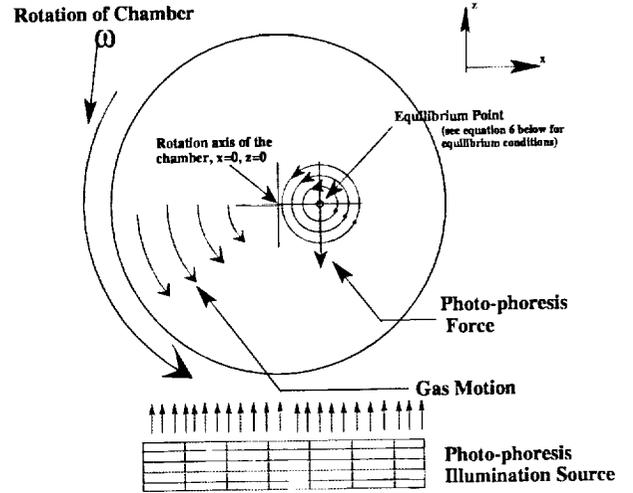


Figure 3. Cylindrical Vacuum Chamber rotating with angular velocity ω .

The response time of the dust particles to the gas motion is

$$\tau_f = s \rho_d / v_t \rho_g \quad (\text{equation 1.0})$$

where s is the particle radius, ρ_d & ρ_g are the densities of the dust and gas respectively, and v_t is the mean thermal velocity of the gas molecules. A one dimensional external force field (the photophoresis field) is added resulting in an acceleration g_z ,

$$g_z = -g - \Omega^2 z \quad (\text{equation 2.0})$$

where g is the mean acceleration and Ω^2 is the acceleration gradient applied in the z direction. Following the mathematics of Klahr & Henning (1997) we have the dust particles orbital radii a at time t ,

$$a = a_0 e^{(\tau_f c t)} \quad (\text{equation 3.0})$$

where a_0 is the initial orbital radius at time $t = 0$ and

$$c = \omega^2 - 1/2 \Omega^2 \quad (\text{equation 4.0})$$

There is a net orbital drift towards the stability point at

$$x_s = \tau_f g / \omega, \quad z=0. \quad (\text{equation 5.0})$$

where the net forces balance if the condition

$$\omega^2 < 1/2 \Omega^2 \quad (\text{equation 6.0})$$

is met. The time scale for the orbital decay τ_c is

$$\tau_c = 1/(\tau_f c) = 1/\{\tau_f (\omega^2 - 1/2 \Omega^2)\}$$

(equation 7.0)

Let us consider a candidate DACS rotating chamber and the parameters that might exist or be imposed:

- Chamber Radius, $L = 5$ cm
- Chamber Temperature, $T = 300^\circ\text{K}$
- Gas Pressure, $P = 1$ mbar
- SiO_2 Particles of size, $S = 1 \mu\text{m}$ radius
- Rotation period = 63 s., or $\omega = 0.1$ radians/s.

we obtain from equation 1.0, the response time of the dust to gas $\tau_f \approx 3$ milliseconds. The mean acceleration has been observed in parabolic flight experiments to be $g \sim 0.1 \text{ m/s}^2$, and the acceleration gradient due to the photophoresis effect will be chosen to be $\Omega^2 \sim 1 \text{ sec}^2$, which indicates that the force field at $z = L$ will be 50% greater than the field at $z = 0$, and 50 % less at $z = -L$ than at $z=0$. Equation 7.0 provides the time scale of the decay, $\tau_c = 680$ seconds, and equation 5.0 gives the orbital stability point at $x_s = 3$ mm.

Under these conditions the stability point will be located a short distance from the cylinder's rotational axis and the decay of the dust orbits will result in a significant concentration of dust at the equilibrium point in a relatively short time. The particles and gas balance changes in the equilibrium region as the particle cloud is concentrated around the equilibrium point a region will be formed having more dust than gas. The behavior of this fluid is not well understood and will require further work during the study phase. The photophoresis effect observed in parabolic flights also became less predicible as the dust aggregates and concentrates. This issue will also be a topic of modeling and study during the course of this investigation.

ACKNOWLEDGEMENT

This research is supported by National Aeronautics and Space Administration DPI C-32055-G. Facilities and equipment to carry out this project have also been provided by the Naval Research Laboratory, the German Space Agency (DLR), the University of Jena, the University of Florida, and the Max Planck Society, to whom we are most grateful. We would also like to acknowledge our fellow investigators on this project: K. Kailasanth, E. Chang, and L. Marlin (NRL), G. Wurm and L.-O. Heim (Univ. Jena), B.A. Gustafson and Y.L. Xu (U of Florida), S. Tehranian (George Mason U.), H.U. Keller (MPI fur Aeronomic).

REFERENCES

1. J. Blum, Coagulation experiments, ASP Conference Series, in press.
2. J. Blum, M. Schnaiter, G. Wurm, M. Rott, The deagglomeration and dispersion of small dust particles - principles and applications, Rev. Sci. Instrum. 67, 589, 1996a.
3. J. Blum, G. Wurm, S. Kempf, Th. Henning, The Brownian motion of dust particles in the solar nebula - an experimental approach to the problem of pre-planetary dust aggregation, Icarus 124, 441, 1996b.
4. F. Deguillon, Photophoresis of suspensions of colored solutions in air and their coefficients of absorption, Comp. Ren. 231, 274, 1950
5. B.A.S. Gustafson, Optical properties of dust from laboratory scattering measurements; Physics, Chemistry, and Dynamics of Interplanetary Dust, ed. Bo A.S.Gustafson and Martha S. Hanner, Astro. Society of the Pacific Press, 1996,
6. Y. Higuchi, N. Sugiura, Determination of size distribution of fluffy aggregates floating in the air, Proc. 3rd Int. Congress on Optical Particle Sizing, 217, 1993.
7. M. Kerker and D.D. Cooke, Photophoretic force on aerosol particles in the free-molecule regime, J. Opt. Soc. Am. 72, 1267, 1982
8. J.A. Nuth, O. Berg, J. Faris, P. Wasilewski, Magnetically enhanced coagulation of very small iron grains, Icarus 107, 155, 1994.
9. Orr, Jr. and E.Y.H.Keng, Photophoretic effects in the stratosphere, J. Atmos. Sci. 21, 475, 1964
10. T. Poppe, J. Blum, Experiments on preplanetary grain growth, Adv. Space Res, in press.
11. G. Praburam and J. Goree, Cosmic dust synthesis by accretion and coagulation, Astrophysical Journal 441, 830, 1995.
12. G. Wurm, J. Blum, Experiments on preplanetary dust coagulation and aggregation, Icarus, submitted.
13. Y. Xu, electromagnetic scattering by an aggregate of spheres, Appl. Opt. 34, 4573., 1995
14. Y. Xu, Calculation of the addition coefficients in electromagnetic multi-sphere scattering theory, J.Comput. Phys., in press